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Quarkonia: a theoretical frame

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Why to study quarkonia

Quarkonia, i.e. bound states made of a heavy quark and a heavy antiquark (like charmonia, bottomonia, ...) are systems where low-energy QCD may be studied in a systematic way (e.g. one may address issues like large-order perturbation theory, non-perturbative matrix elements, QCD vacuum, exotica, confinement, deconfinement, ...). This is because $M \gg p \gg E$, where M is the heavy-quark mass, p the momentum transfer and E the binding energy of the bound state, and because $M \gg \Lambda_{\rm QCD}$, the scale of non-perturbative QCD.

(1) $M \gg p \gg E$ implies that quarkonia are non-relativistic and characterized by the hierarchy of scales typical of a non-relativistic bound state:

$$M \gg p \sim 1/r \sim Mv \gg E \sim Mv^2, \qquad (1)$$

where r is the typical distance between the heavy quark and the heavy antiquark and $v \ll 1$ is the typical heavy-quark velocity. Systematic expansions in v may be implemented at the Lagrangian level by constructing suitable effective field theories (EFTs): expanding QCD in p/M and E/M leads to NRQCD [1]; expanding NRQCD in $E\,r$ leads to pNRQCD [2]. The hierarchy of non-relativistic scales makes the very difference of quarkonia from heavy-light mesons, which are characterized by just two scales: M and $\Lambda_{\rm QCD}$ [3]. For a review of non-relativistic effective field theories we refer to [4]. Some historical background has been discussed in [5].

(2) $M \gg \Lambda_{\rm QCD}$ implies $\alpha_{\rm s}(M) \ll 1$: phenomena happening at the scale M may be treated perturbatively. We may further have small couplings if $Mv \gg \Lambda_{\rm QCD}$ and $Mv^2 \gg \Lambda_{\rm QCD}$, in which case $\alpha_{\rm s}(Mv) \ll 1$ and $\alpha_{\rm s}(Mv^2) \ll 1$ respectively. This is likely to happen only for the lowest charmonium and bottomonium states (see Fig. 1).

It is precisely the rich structure of separated energy scales that makes quarkonium an ideal probe of confinement and deconfinement. The different quarkonium radii are differently sensitive to the Coulombic and confining interaction (see Fig. 2). Hence, different quarkonia will dissociate in a medium at different temperatures, providing a thermometer for the plasma [7, 8].

All quarkonium scales get entangled in a typical amplitude involving a quarkonium observable, see Fig. 3. In particular, quarkonium annihilation and production happen at the scale M, quarkonium binding happens at the scale

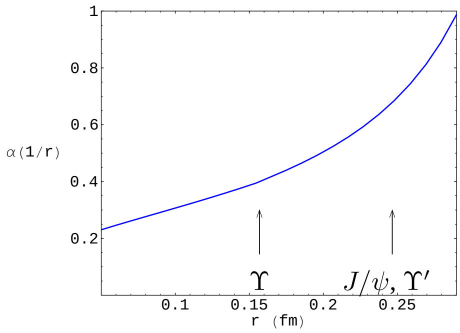

Figure 1: $\alpha_{\rm s}$ running at one loop and $\alpha_{\rm s}(M_{J/\psi}v_{J/\psi})$ and $\alpha_{\rm s}(M_{\Upsilon(1S)}v_{\Upsilon(1S)})$.

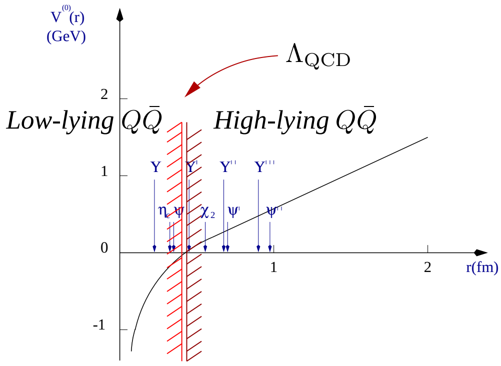

Figure 2: Static potential vs quarkonium radii taken from [6].

Mv, which is the typical momentum exchanged inside the bound state, while very low-energy gluons and light quarks (also called ultrasoft degrees of freedom) live long enough that a bound state has time to form and, therefore, are sensitive to the scale Mv^2. Ultrasoft gluons are responsible for phenomena like the Lamb shift in QCD.

Physics at the scale M

Quarkonium annihilation and production happen at the scale M. The suitable EFT is NRQCD, which follows from QCD by integrating out the scale M, see Fig. 4. As a consequence, the effective Lagrangian is organized as an expansion in $1/M$ and $\alpha_{\rm s}(M)$:

$$\mathcal{L}_{\rm NRQCD} = \sum_n \frac{c_n(\alpha_{\rm s}(M),\mu)}{M^n} \times O_n(\mu, Mv, Mv^2, ...), \qquad (2)$$

where O_n are the operators of NRQCD that live at the low-energy scales Mv and Mv^2, μ is the NRQCD factorization

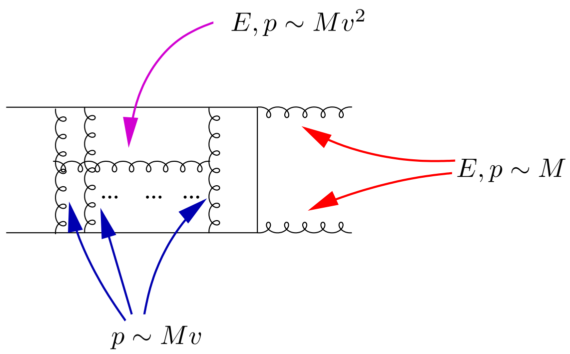

Figure 3: Typical scales appearing in a quarkonium annihilation diagram.

Ratio	PDG09	LO	NLO
$\frac{\Gamma_{\chi_{c0}\to\gamma\gamma}}{\Gamma_{\chi_{c2}\to\gamma\gamma}}$	≈ 4.9	3.75	≈ 5.43
$\frac{\Gamma_{\chi_{c2}\to\mathrm{l.h.}}-\Gamma_{\chi_{c1}\to\mathrm{l.h.}}}{\Gamma_{\chi_{c0}\to\gamma\gamma}}$	≈ 440	≈ 347	≈ 383
$\frac{\Gamma_{\chi_{c0}\to\mathrm{l.h.}}-\Gamma_{\chi_{c1}\to\mathrm{l.h.}}}{\Gamma_{\chi_{c0}\to\gamma\gamma}}$	≈ 4000	≈ 1300	≈ 2781
$\frac{\Gamma_{\chi_{c0}\to\mathrm{l.h.}}-\Gamma_{\chi_{c2}\to\mathrm{l.h.}}}{\Gamma_{\chi_{c2}\to\mathrm{l.h.}}-\Gamma_{\chi_{c1}\to\mathrm{l.h.}}}$	≈ 8.0	2.75	≈ 6.63
$\frac{\Gamma_{\chi_{c0}\to\mathrm{l.h.}}-\Gamma_{\chi_{c1}\to\mathrm{l.h.}}}{\Gamma_{\chi_{c2}\to\mathrm{l.h.}}-\Gamma_{\chi_{c1}\to\mathrm{l.h.}}}$	≈ 9.0	3.75	≈ 7.63

Table 1: Comparison of decay width ratios of χ_{cJ} from [13] (l.h. stands for light hadrons) with LO and NLO determinations (without corrections of relative order v^2, $m_c = 1.5$ GeV and $\alpha_s(2m_c) = 0.245$).

scale and c_n are the Wilson coefficients of the EFT that encode the contributions from the scale M and are non-analytic in M.

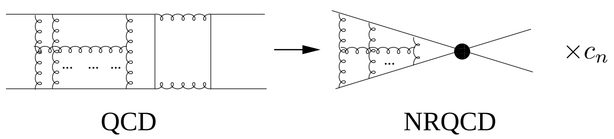

Figure 4: Matching of the diagram of Fig. 3 to NRQCD.

The NRQCD factorization formula for the quarkonium annihilation width (into light hadrons or photons or lepton pairs) reads:

$$\Gamma_{H\ \mathrm{annihilation}} = \sum_n \frac{2\,\mathrm{Im}\, c_n}{M^{d_{O_n}-4}} \langle H | O_n^{4-\mathrm{fermion}} | H \rangle, \tag{3}$$

where d_{O_n} is the dimension of the four-fermion operator $O_n^{4-\mathrm{fermion}}$. Recently, substantial progress has been made in the evaluation of the factorization formula at order v^7 [9, 10], in the lattice evaluation of the NRQCD matrix elements $\langle H|O_n^{4-\mathrm{fermion}}|H\rangle$ [11] and in the data of many hadronic and electromagnetic decays [12]. As it was already discussed in [12], the data are clearly sensitive to NLO corrections in the Wilson coefficients c_n (and presumably also to relativistic corrections). For an updated list of ratios of P-wave charmonium decay widths, see Tab. 1

The high precision of data and matrix elements has been recently exploited to provide a new determination of α_s from $\Gamma_{\Upsilon(1S)\to\gamma\,\mathrm{l.h.}}/\Gamma_{\Upsilon(1S)\to\mathrm{l.h.}}$ [14]:

$$\alpha_s(M_{\Upsilon(1S)}) = 0.184^{+0.015}_{-0.014}, \qquad \alpha_s(M_Z) = 0.119^{+0.006}_{-0.005}. \tag{4}$$

Recent progress in quarkonium production in the framework of the NRQCD factorization have been discussed in [15].

Physics at the scales Mv and Mv^2

Quarkonium formation happens at the scale Mv. The suitable EFT is pNRQCD [2], which follows from NRQCD by integrating out the scale Mv, see Fig. 5. As a consequence, the effective Lagrangian is organized as an expansion in $1/M$ and $\alpha_s(M)$, inherited from NRQCD, and an expansion in r:

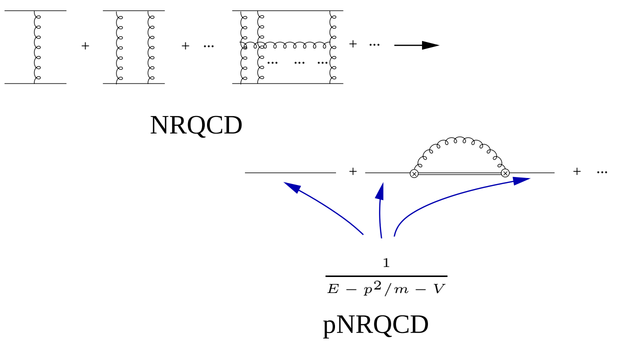

Figure 5: Matching of the diagram of Fig. 4 to pNRQCD.

$$\mathcal{L}_{\mathrm{pNRQCD}} = \int d^3r \sum_n \sum_k \frac{c_n(\alpha_s(M),\mu)}{M^n} \times V_{n,k}(r,\mu',\mu)\; r^k \times O_k(\mu', Mv^2, \ldots), \tag{5}$$

where O_k are the operators of pNRQCD that live at the low-energy scale Mv^2, μ' is the pNRQCD factorization scale and $V_{n,k}$ are the Wilson coefficients of the EFT that encode the contributions from the scale r and are non-analytic in r. Looking at the equations of motion of pNRQCD, we may identify $V_{n,0}$ with the $1/M^n$ potentials that enter the Schrödinger equation and $V_{n,k\neq 0}$ with the couplings of the ultrasoft degrees of freedom, which provide corrections to the Schrödinger equation.

The static QCD spectrum without light quarks

The spectrum of a static quark and a static antiquark has been studied in QCD without light quarks on the lattice, for instance in [16]. At short distances, it is well described by the Coulomb potential in the colour-singlet or in the colour-octet configurations: $V_s = -4\alpha_s/3r$ and $V_o = \alpha_s/6r$. At

large distances, the energies rise linearly with r. Higher excitations develop a mass gap of order $\Lambda_{\rm QCD}$ with respect to the lowest one. Reintroducing the heavy-quark mass M, the spectrum of the Mv^2 fluctuations around the lowest state constitutes the quarkonium spectrum while the spectrum of the Mv^2 fluctuations around the higher excitations constitutes the hybrid spectrum.

Quarkonia

The energy of the lowest excitation between a static quark and a static antiquark is the quarkonium static energy. Quarkonia may be identified with the Mv^2 spectrum that differentiates once $1/M$ corrections (first of all the kinetic energy) are added to the effective Lagrangian, which reads

$$\begin{aligned} \mathcal{L}_{\rm pNRQCD} &= \int d^3r\, S^\dagger \left(i\partial_0 - \frac{p^2}{M} - V_s + ... \right) S \\ &\quad + \text{ultrasoft d.o.f.}, \end{aligned} \tag{6}$$

where S is the colour-singlet quarkonium field.

At short distances, the static potential is well described by perturbation theory up to NNNLL accuracy (for a recent analysis see [17]). Therefore the lowest-lying quarkonium states have a radius that is small enough for perturbation theory to apply (see Fig. 1). Higher-order corrections to the spectrum, masses and wave functions have been calculated in [18]. Non-perturbative corrections are small and encoded in (local or non-local) condensates. Many parameters and observables of the lowest quarkonium states have been calculated. They include: c and b masses at NNLO and partially at N^{3}LO (for a review see [12], a more recent result is in [19]); B_c mass at NNLO [20]; B_c^*, η_c, η_b masses at NLL [21]; quarkonium $1P$ fine splittings at NLO [22]; $\Upsilon(1S)$, η_b electromagnetic decays at NNLL [23]; $\Upsilon(1S)$ and J/ψ radiative decays at NLO [25]; $\Upsilon(1S) \to \gamma\eta_b$, $J/\psi \to \gamma\eta_c$ at NNLO [24]; $t\bar{t}$ cross section at NNLO [26]; leading thermal effects on a quarkonium in medium: masses, widths, [27], ... For some recent reviews, we refer to [28, 29].

High-lying quarkonia are the Mv^2 fluctuations around the long-range tail of the potential. The long-range tail of the potential is not accessible by perturbation theory (see Fig. 1). However, the potential may still be expanded in $1/M$ and each term of the expansion can be expressed in terms of field-strength insertions on a static Wilson loop [30], which can be calculated on the lattice [31]. The resulting potential may be used in (6). The solution of the corresponding Schrödinger equation provides the quarkonium masses and wave functions. A trivial example of application of this method is the mass of the h_c. The lattice data show a vanishing long-range component of the spin-spin potential so that the potential appears to be entirely dominated by its short-range, delta like, part. This suggests that the $^1P_1$ state should be close to the centre of gravity of the ^3P_J system. Indeed, the measured mass of the h_c by CLEO, $M_{h_c} = 3524.4 \pm 0.6 \pm 0.4$ MeV [32], and E835, $M_{h_c} = 3525.8 \pm 0.2 \pm 0.2$ MeV [33], is just on the top of the mass of the 1^3P_J centre of gravity: $M_{\rm c.o.g.}(1^3P_J) = 3525.36 \pm 0.2 \pm 0.2$ MeV.

Gluonic excitations of quarkonia

Many states, built on each of the hybrid potentials, are expected. These states typically develop a width also without including light quarks, since they may decay into lower states, e.g. like hybrid $\to$ glueball + quark-antiquark.

One possible candidate for such a state is the $Y(4260)$. The $Y(4260)$ has been discovered by BABAR in the radiative return process $e^+e^- \to \gamma\pi^+\pi^- J/\psi$ with mass $M_Y = 4259 \pm 8^{+2}_{-6}$ MeV and width $\Gamma = 88 \pm 23^{+6}_{-4}$ MeV [34], and seen in the same process by BELLE with mass $M_Y = 4247 \pm 12^{+17}_{-32}$ MeV and width $\Gamma = 108 \pm 19 \pm 10$ MeV [35] and by CLEO with mass $M_Y = 4284^{+17}_{-16} \pm 4$ MeV and width $\Gamma = 73^{+39}_{-25} \pm 5$ MeV [36]. CLEO has also confirmed the existence of an enhancement in the $\pi^+\pi^- J/\psi$ cross section at 4260 MeV in a measurement of direct e^+e^- annihilation at $\sqrt{s} = 4040$, 4160 and 4260 MeV [37]. The $Y(4260)$ J^{PC} quantum numbers are 1^{--}. BABAR measures $\mathcal{B}(Y \to D\bar{D})/\mathcal{B}(Y \to J/\psi\pi^+\pi^-) < 1.0$ (≈ 500 for $\psi(3770)$, which suggests an exotic interpretation for the $Y(4260)$) [38], moreover $\mathcal{B}(Y \to D^*\bar{D})/\mathcal{B}(Y \to J/\psi\pi^+\pi^-) < 34$ and $\mathcal{B}(Y \to D^*\bar{D}^*)/\mathcal{B}(Y \to J/\psi\pi^+\pi^-) < 40$ [39].

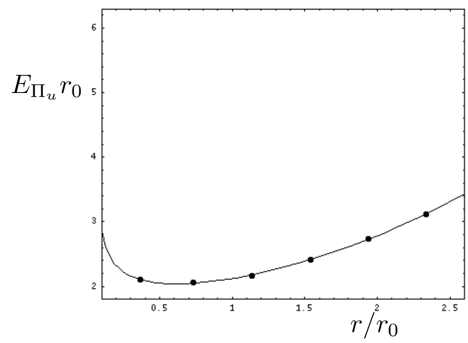

Figure 6: The hybrid static potential Π_u at short and intermediate distances, $r_0 \approx 0.5$ fm. The points are the lattice data from [16], the continuous line is the fitting curve $E_{\Pi_u} r_0 = \text{constant} + 0.11\, r_0/r + 0.24\, (r/r_0)^2$.

Many interpretations have been proposed for the $Y(4260)$, one of this is that the $Y(4260)$ is a charmonium hybrid [40, 41, 42]. If the $Y(4260)$ is interpreted as a charmonium hybrid, one may rely on the heavy-quark expansion and on lattice calculations to study its properties. Decays into $D^{(*)}\bar{D}^{(*)}$ should be suppressed, since they are forbidden at leading order in the heavy-quark expansion [41]. This is in agreement with the upper limit on $Y \to D\bar{D}$ reported by BABAR. The quantum numbers of the $Y(4260)$ are consistent with those of a pseudoscalar 0^{-+} fluctuation $|\phi\rangle$ belonging to the family of Mv^2 fluctuations around the gluonic excitation between a static quark and a static antiquark with quantum numbers 1^{+-}, also

known as Π_u,

$$|Y\rangle = |\Pi_u\rangle \otimes |\phi\rangle. \tag{7}$$

It is suggestive that, according to lattice calculations [16], Π_u is the lowest gluonic excitation between a static quark and a static antiquark above the quark-antiquark colour singlet. $|\phi\rangle$ may be obtained as the solution of the Schrödinger equation whose potential is the static energy of Π_u. Fitting the static energy of Π_u at short and intermediate distances, one gets $E_{\Pi_u} r_0 = \text{constant} + 0.11\, r_0/r + 0.24\,(r/r_0)^2$, see Fig. 6. Solving the corresponding Schrödinger equation, one gets $M_Y = 2\times 1.48 + 0.87 + 0.53 = 4.36$ GeV, where 1.48 GeV is the charm mass in the RS scheme [43] and 0.87 GeV is the gluelump mass in the same scheme [44].

The QCD spectrum with light quarks

Adding light quarks changes the heavy quark-antiquark spectrum in the following way (see J. Soto in [45]).

(1) We still have states made just of heavy quarks and gluons. They may develop a width because of the decay through pion emission. If new states made with heavy and light quarks develop a mass gap of order $\Lambda_{\rm QCD}$ with respect to the former ones, then these new states may be absorbed into the definition of the potentials or of the (local or non-local) condensates [46].

(2) In addition, new states built using the light quark quantum numbers may form. Possible states made of two heavy and light quarks include states built on the pair of heavy-light mesons ($D\bar{D}$, $B\bar{B}$, ...), molecular states [47], molecular states made of the usual quarkonium states, built on the static potential, and light hadrons (hadro-quarkonium) [48], pairs of heavy-light baryons [49], tetraquark states [50] and likely many other states.

Clear evidence for four-quark states may be provided by a charged resonance, like the $Z^+(4430)$, $Z_1^+(4050)$ and $Z_2^+(4250)$ signals, detected by BELLE (but not confirmed by BABAR), possibly are. See [51, 52] and the panel discussion at this conference.

There is accumulating evidence, although not yet conclusive, that the $X(3872)$ may be a four quark state. The state $X(3872)$ has been discovered by BELLE in $B^\pm \to K^\pm X \to K^\pm \pi^+\pi^- J/\psi$ with $M_X = 3872.0 \pm 0.6 \pm 0.5$ MeV [53], and confirmed by BABAR [54] that measures $M_X = 3871.4 \pm 0.6 \pm 0.1$ MeV in $B^+ \to K^+\pi^+\pi^- J/\psi$ and $M_X = 3868.7 \pm 1.5 \pm 0.4$ MeV in $B^0 \to K^0\pi^+\pi^- J/\psi$ [55]. The state has also been seen at the Tevatron in $p\bar{p} \to X \to \pi^+\pi^- J/\psi$ by CDF with a mass $M_X = 3871.3 \pm 0.7 \pm 0.4$ MeV [56] and by D0 with a mass $M_X = 3871.8 \pm 3.1 \pm 3.0$ MeV [57]. BELLE has an upper limit on the width: $\Gamma < 2.3$ MeV, while BABAR finds $\Gamma = 3.0^{+1.9}_{-1.4} \pm 0.9$ MeV [58]. The $X(3872)$ has been detected in different decay modes, the decay $X \to D^0\bar{D}^0\pi^0$ being likely the dominant one: $\mathcal{B}(X \to D^0\bar{D}^0\pi^0)/\mathcal{B}(X \to \pi^+\pi^- J/\psi) = 9.4^{+3.6}_{-4.3}$ [59]. One should notice that BELLE finds a threshold enhancement peak in the $D^0\bar{D}^0\pi^0$ invariant mass at $3875.4 \pm 0.7^{+1.2}_{-2.0}$ MeV, which is about $2\,\sigma$ larger than the world-average mass of the $X(3872)$. The decay mode $X \to \gamma J/\psi$ [60] implies that the $X(3872)$ has positive charge conjugation. Analyses of angular distributions performed by BELLE [61] and CDF [62] favor a spin parity assignment 1^+. The ratio $\mathcal{B}(X \to \pi^+\pi^-\pi^0 J/\psi)/\mathcal{B}(X \to \pi^+\pi^- J/\psi) = 1.0 \pm 0.4 \pm 0.3$ measured by BELLE [60] suggests that the $X(3872)$ is a mixture of isospin $I = 1$ and $I = 0$ states. The substantial $I = 1$ component requires that the $X(3872)$ contains $u\bar{u}/d\bar{d}$ pairs in addition to hidden charm, which thus qualifies it as a four-quark state [63]. Hence, most recently, the majority of theoretical studies has analyzed the $X(3872)$ as a four-quark state with J^{PC} quantum numbers 1^{++}. See Fig. 7.

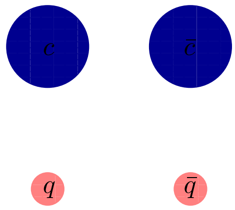

Figure 7: $c\bar{c}q\bar{q}$ 4-quark state.

Three quark-pair configurations are possible for a four-quark state of the type $c\bar{c}q\bar{q}$ (q stands for a generic light quark). All of them have been exploited in the literature. However, the resulting models are not equivalent, because different dynamics are attributed to different configurations.

Clearly, for states made of heavy quark-antiquark pairs and light quarks, it would be useful to have the spectrum of tetraquark potentials, like the one that we have for the gluonic excitations and that we discussed above. It would allow us to build a plethora of states on each of the potentials, many of them developing a width due to decays through pion (or other light hadron) emission. Diquarks have been recently investigated on the lattice [64]. In the lack of further theoretical input from QCD, many tetraquark studies rely on phenomenological models of the tetraquark interaction unless some special hierarchy of dynamical scales may be further exploited on the top of the non-relativistic and perturbative expansions discussed so far.

In [65], see Fig. 8, it is assumed that $X \sim (c\bar{c})^8_{S=1}(q\bar{q})^8_{S=1}$, i.e. that the dominant Fock-space component contains a $c\bar{c}$ pair and a $q\bar{q}$ pair in a colour-octet configuration with spin 1. Calculations have been based on a phenomenological interaction Hamiltonian.

In [66], see Fig. 9, it is assumed that $X \sim (cq)^{\bar{3}}_{S=1}(\bar{c}\bar{q})^3_{S=0} + (cq)^{\bar{3}}_{S=0}(\bar{c}\bar{q})^3_{S=1}$. Here, the clustering of quark pairs in tightly bound colour-triplet diquarks is not induced by a scale separation as it would happen in baryons made of two heavy quarks [67], but is a dynamical assumption of the model. In particular, the model pre-

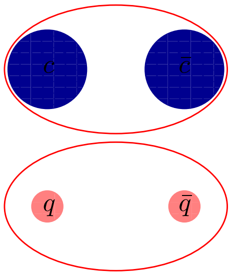

Figure 8: $c\bar{c}q\bar{q}$ 4-quark state in the configuration of [65].

dicts the existence of two neutral states made of $cu\bar{c}\bar{u}$ (X_u) and $cd\bar{c}\bar{d}$ (X_d) and of two charged ones. The two resonances discovered by BELLE and BABAR, the first decaying in $J/\psi\,\pi^+\pi^-$ and the second preferably in $D^0\bar{D}^0\pi^0$ have been suggested as possible candidates for the X_d and X_u [68].

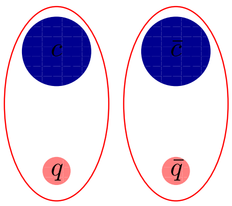

Figure 9: $c\bar{c}q\bar{q}$ 4-quark state in the configuration of [66].

In [69, 70], see Fig. 10, it is assumed that $X \sim (c\bar{q})^1_{S=0}(q\bar{c})^1_{S=1} + (c\bar{q})^1_{S=1}(q\bar{c})^1_{S=0} \sim D^0\,\bar{D}^{*\,0} + D^{*\,0}\,\bar{D}^0$, i.e. that the dominant Fock-space component of the $X(3872)$ is a $D^0\,\bar{D}^{*\,0}$ and $D^{*\,0}\,\bar{D}^0$ molecule; small short-range components of the type $(c\bar{c})^1_{S=1}(q\bar{q})^1_{S=1} \sim J/\psi\,\rho,\omega$ are included as well. Predictions depend on the adopted phenomenological Hamiltonian, which typically contains, in the short range ($\sim 1/\Lambda_{\rm QCD}$), potential-type interactions among the quarks and, in the long range ($\sim 1/m_\pi$), the one-pion exchange. The prediction $\Gamma(X \to \pi^+\pi^- J/\psi) \approx \Gamma(X \to \pi^+\pi^-\pi^0 J/\psi)$ made in [70] turned out to be consistent with the BELLE result [60]. However, another prediction, $\Gamma(X \to \pi^+\pi^- J/\psi) \approx 20\,\Gamma(X \to D^0\bar{D}^0\pi^0)$, is two orders of magnitude far from the data [59]. Not necessarily this points to a failure of the molecular model, but possibly to a smaller $J/\psi\,\rho$ component in the $X(3872)$ Fock space.

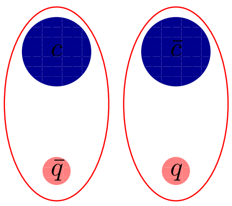

Figure 10: $c\bar{c}q\bar{q}$ 4-quark state in the configuration of [69, 70].

In [71, 72, 73], see Fig. 11, it is assumed not only that the $X(3872)$ is a $D^0\,\bar{D}^{*\,0}$ and $\bar{D}^0\,D^{*\,0}$ molecule, but also that it is loosely bound, i.e. that the following hierarchy of scales is realized: $\Lambda_{\rm QCD} \gg m_\pi \gg m_\pi^2/M_{D_0} \approx 10$ MeV $\gg E_{\rm binding}$. Indeed, the binding energy, $E_{\rm binding}$, which may be estimated from $M_X - (M_{D^{*0}} + M_{D^0})$, is very close to zero, i.e. much smaller than the natural scale m_π^2/M_{D_0}. This is also the case when using a recent CLEO determination of the D_0 mass, $M_{D_0} = 1864.847 \pm 0.150 \pm 0.095$ MeV [74]. The main uncertainty comes from the $X(3872)$ mass. Systems with a short-range interaction and a large scattering length have universal properties that may be exploited: in particular, production and decay amplitudes factorize in a short-range and a long-range part, where the latter depends only on one single parameter, the scattering length. The long-range molecular $D^0\,\bar{D}^{*\,0}$ and $\bar{D}^0\,D^{*\,0}$ components of the $X(3872)$ should be responsible for the $X(3872)$ decaying into $D^0\bar{D}^0\pi^0$. For a recent analysis of the BELLE data about the $D^0\bar{D}^0\pi^0$ final state enhancement and the molecular picture we refer to [75]. For discussion about the evaluation of the $X(3872)$ production cross section at the Tevatron inside the molecular model we refer to [76, 77].

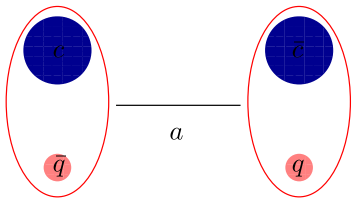

Figure 11: $c\bar{c}q\bar{q}$ 4-quark state in the configuration of [71, 72, 73].

Coupled channels

An important (and yet unsolved) problem is how all the different kind of states (with and without light quarks) interact with each other. A systematic treatment does not exist so far. For the coupling with two-meson states, most of the existing analyses rely on two models, which are now more than 30 years old: the Cornell coupled-channel model [78] and the $^3P_0$ model [79]. Steps towards a lattice based approach have been undertaken recently [80, 81] and may, in perspective, provide an alternative, QCD based, treatment.

Conclusions

Our understanding of how a (effective field) theory of quarkonium should look like has dramatically increased over the last decade.

For states below threshold such a theory exists and allows a systematic study of the quarkonium lowest resonances. Even precision physics is possible. Higher resonances may need to be supplemented by lattice data. High-quality lattice data have become available in the last years

for some crucial quantities (e.g. potentials, decay matrix elements, ...).

For states above threshold, the picture appears much more uncertain. Many degrees of freedom seem to be present, and the absence of a clear systematics is an obstacle to an universal picture. Most likely, systematic descriptions will be found that suite only specific families of states, the near-threshold molecular states providing an example.

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